LASER SHEAROGRAPHIC TESTING OF FOAM INSULATION ON CRYOGENIC FUEL TANKS

Douglas D. Burleigh
James E. Engel
David R. Kuhns

General Dynamics Space Systems Division
P.O. Box 85990
Mail Zone 23-8560
San Diego, CA 92186

INTRODUCTION

The Centaur is a high-energy rocket used as a second stage to the Atlas launch vehicle. The Centaur is cryogenically fueled, using liquid hydrogen and liquid oxygen, and requires insulation to prevent fuel boiloff prior to launch. The original insulation system used on Centaur is a set of fiberglass honeycomb panels, which are jettisoned after launch. These panels are still used on the Atlas I version of Atlas/Centaur.

The newer Atlas II version uses a 0.6-inch-thick closed-cell PVC (polyvinyl chloride) (fixed) foam insulation, which is adhesively bonded directly to the pressure-stabilized, 10-foot-diameter, 0.016-inch-thick stainless steel tank. The area of the foam is approximately 600 ft^2. During the qualification of this new insulation system, an NDT method was required to verify the integrity of the adhesive bond between the foam and the tank.

Figure 1 shows the insulation systems of Atlas I and II.

The requirements placed on the selection of the NDT method were as follows:

- Noncontact (to prevent damage to test article)
- Portable for use on launch platforms
- Inspections to be conducted from the exterior (foam side) only
- The tank may not be filled with water
- Minimum detectable disbond sizes of 4 in.
- Inspection rates of 10 ft^2 per hour over an area of 600 ft^2
- Technique identification, development, and validation within five months

Since we were unsure of our prospects for success in satisfying all requirements stated above, we also considered NDT methods from the steel side; if no method were found that worked from the foam side, a case could be made for allowing access to the interior of the tank.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

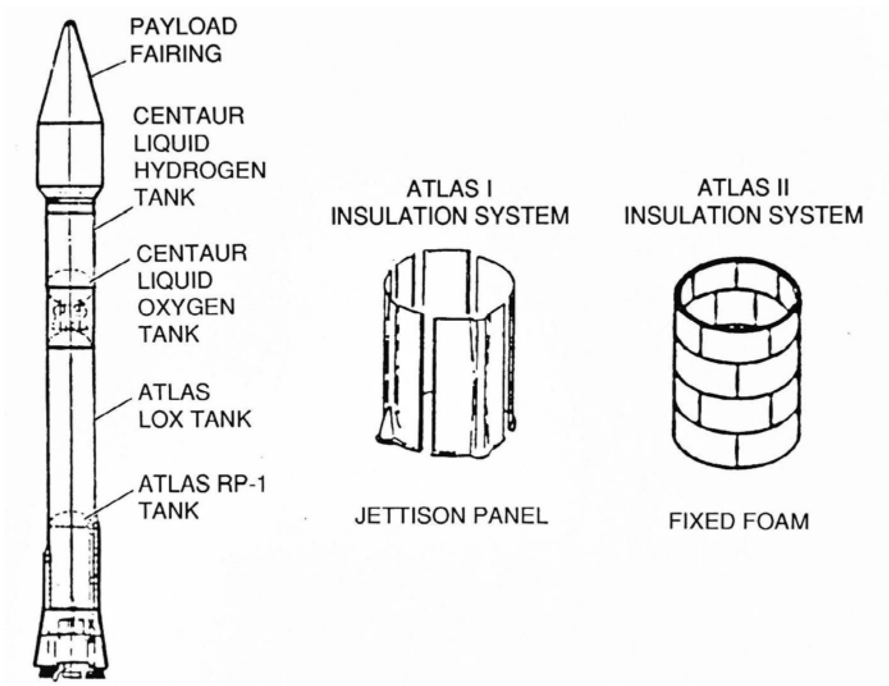

Fig. 1. A fixed foam insulation system replaces the jettisonable insulation panel configuration.

In order to evaluate NDT methods, a series of test panels containing planned disbonds, created by an absence of adhesive, were constructed. A list of NDT methods considered is shown in Table 1.

Table 1. NDT methods considered for fixed foam.

Acoustic methods	Mechanical methods
Ultrasonic C-scan	Vacuum pull
Leaky lamb waves	Fluid injection
Coin tap techniques	Mechanical attachment
Mechanical impedance	Radiographic methods
Thermographic methods	Neutron
LN_2 spray or fill	X-ray
Xenon flash lamp	Backscatter
Quartz lamps	
Interferometric methods	
Laser holography	
Moiré interferometry	
Electronic laser shearography	

Some of these methods were capable of detecting the disbonds in the NDT standard, but most required unacceptable conditions, such as access to the inside of the tank (i.e., some methods worked, but only from the metal side).

The most promising of these techniques, based on preliminary testing of the NDT standard, was laser shearography, which was selected for further development.

Laser shearography is a modified form of laser interferometry that detects very small displacements of a surface when stress is applied. The surface is illuminated with a diffused laser beam (argon, in our case), and a CCD (charge coupled device) video camera views the laser-illuminated surface through an optical shearing device. This may be a birefringent crystal, an optical wedge, or a system of mirrors.

A video image is captured in electronic memory, the part is stressed, another image is entered into memory, and the two images are subtracted. The differences between the two images represent displacements of the surface caused by the applied stress. The shearographic image represents the derivative of the curvature of the observed surface with respect to the direction of the optical shearing. This differs from other holographic methods in which the image consists of fringe lines of equal displacement. If the stress mechanism and amplitude are judiciously chosen, the shearographic process will reveal subsurface flaws and disbonds in materials. More detailed explanations of the theory of shearography may be found in the references.

The primary advantage of laser shearography over more conventional interferometric techniques is that shearography is much less susceptible to vibration. This allows shearography to be used in testing in a factory or "field" environment rather than in a laboratory equipped with vibration isolation tables.

In our work, acoustic excitation was used in preliminary shearographic tests of flat NDT standard panels and vacuum stressing was later used in actual inspections of the tanks. Other possible stress mechanisms include thermal, magnetic, mechanical loading, change in pressure (positive or negative), etc.

A shearographic image of a 3 x 3 inch square artificial disbond in a standard panel is shown in Figure 2. Acoustic excitation was used to create this image.

Early work included mathematical predictions of resonant frequencies of square and round foam disbonds from 1 to 10 inches across. These predictions

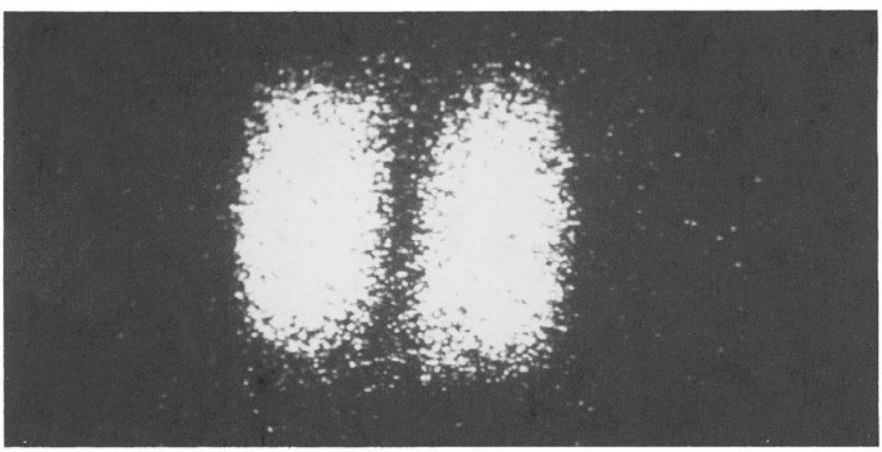

Fig. 2. Electronic shearographic image of a 3 x 3 inch square disbond between foam and stainless in a flat test panel.

compared favorably with acoustically excited shearographic tests of simulated foam disbonds on test panels.

Full-Scale Tests

After considerable developmental testing and improvements to the equipment, the following technique was established. A low-profile vacuum box, with a 1-inch-thick clear plexiglass lid and an open back contoured to mate with the cylindrical surface of the Centaur tank, was constructed. This box was held onto the surface of the foam by using a vacuum blower to maintain a negative pressure of approximately 0.5 psi. The first shearographic image was recorded in this configuration. The pressure in the box was reduced to approximately -1.0 psi below ambient and the second image was recorded and subtracted from the first. A photo of the box is shown in Figure 3. The box was framed with a soft foam to prevent damage to the foam insulation on the Centaur.

A schematic of the test apparatus is shown in Figure 4.

Figure 5 shows the test in process. Three Centaurs were tested in San Diego in this configuration. The tests were performed in a building specifically constructed for the application of the foam insulation. The Centaur tanks are supported vertically. An annular work platform surrounds the tank and is moveable vertically. The equipment was set up and, using the moveable platform, a vertical row of foam was inspected. The equipment was then moved around the circumference of the tank and another vertical row was inspected. This scanning process was continued until the entire tank was inspected; it required approximately 24 hours.

Two difficulties were encountered in these tests. First, the test had to be conducted in darkness since the vacuum box permitted the ingress of ambient light, which reduced the effectiveness of the method. Second, the elevator work platform was suspended in a manner that occasionally permitted movement in the test plane. Despite the relative insensitivity of shearography to motion, the motion of the platform was occasionally a problem.

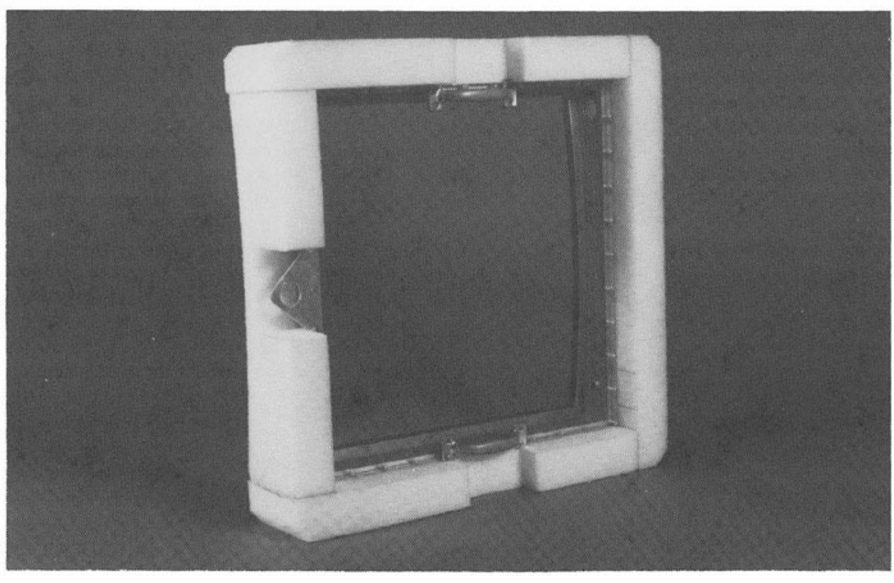

Fig. 3. Vacuum test box.

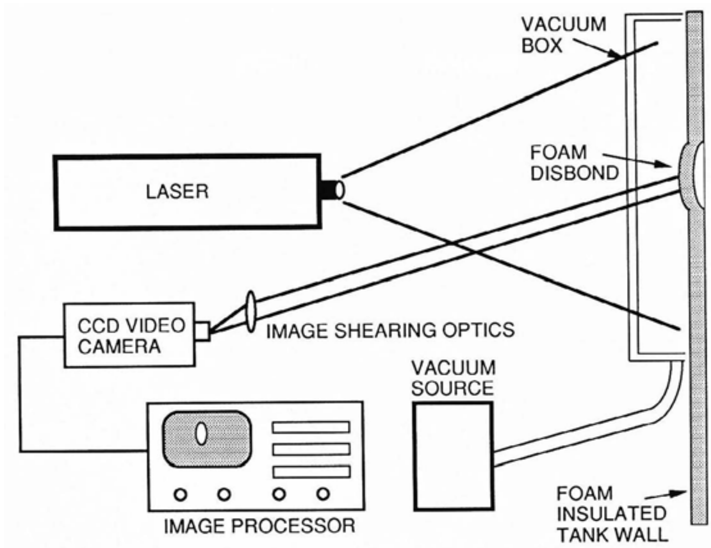

Fig. 4. Laser shearography schematic.

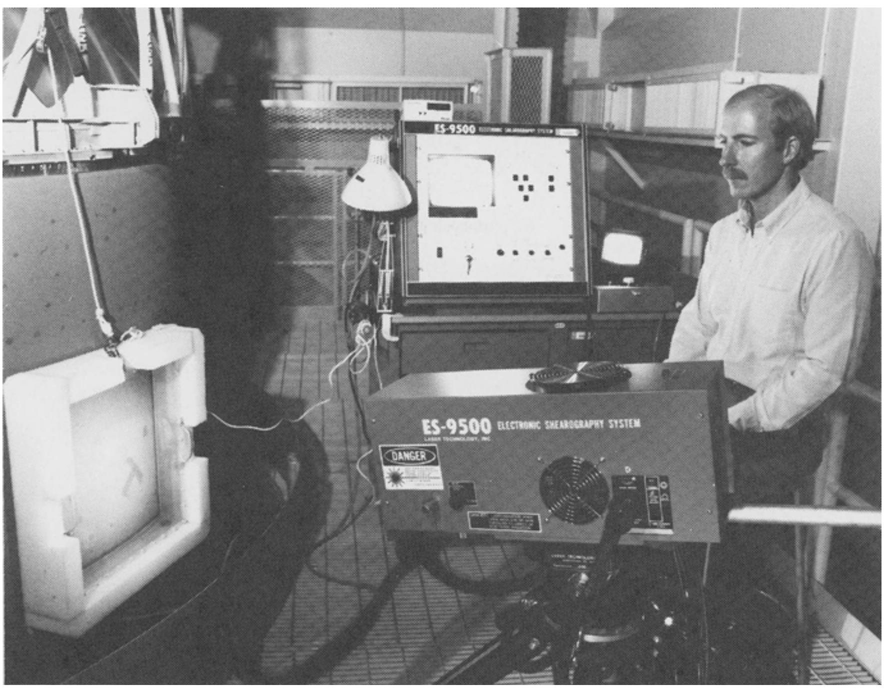

Fig. 5. Laser shearography test in progress (San Diego).

NDT Standard

A large NDT standard was constructed to verify the test method both before and after each test session. The standard consists primarily of a 3 x 3 foot piece of half-inch-thick aluminum, roll-formed to match the curvature of the Centaur tank. A layer of rubber is bonded to the aluminum and on top of this is a 0.016-inch-thick stainless steel sheet, which is held under tension to simulate the stress of the Centaur tank skin while under pressurization. A layer of foam was adhesively bonded to the skin. A series of artificial disbonds was built into the foam/skin bondline. The disbonds range in size from a 1 x 1 inch square to a 7 x 15 inch triangle. The NDT standard with its support structure was rather heavy and was mounted on wheels.

Shearographic Testing on the Launch Pad at Cape Canaveral

The next phase of testing was to be performed on the launch pad at Cape Canaveral with the Centaur mounted atop the Atlas. The purpose of the testing was to verify that disbonds in the adhesive layer were not caused by the thermal cycling, which occurs when the tank is filled with cryogenic fluids and then emptied during routine prelaunch testing.

The launch tower has fixed work platforms, which are separated by up to 12 feet in height. Inspecting the foam near the top of one stage would have required supporting the laser at a height of approximately nine feet. And the equipment would have needed to be respositioned frequently, which would have required considerably more inspection time.

The solution to these problems was the addition to the shearography system of an optical fiber connector that carries the laser beam. This allows the laser to be remotely located and provides much greater portability. The optical fiber is single-mode, has a diameter of 4 μ, and is armor-clad for mechanical protection.

The flat vacuum box was replaced with a conical metal vacuum hood. Inside the hood is a laser projection lens, the shearing crystal, and a miniature CCD video camera. An umbilical, which is made up of a corrugated vacuum hose, the fiberoptic laser connector, and a video cable, goes between the hood and the remotely located control and image processing systems. The hood is the only part of the system that must be moved routinely; this provides tremendous portability compared to the original configuration.

This modified system completely excludes light, allowing testing under any lighting conditions; darkness is no longer necessary. And relative motion between the test surface and the work platform is no longer a problem since the laser is essentially attached to the tank during testing. The only disadvantage is that the fiber optical cable absorbs some of the laser energy and thus reduces the illumination power. The absorption is a function of cable length. With our 25-foot cable, sufficient power remained to inspect an area approximately equal to the area inspected by the vacuum box previously used.

A schematic diagram of the modified system is shown in Figures 6 and 7. Figure 8 shows the system in use at Cape Canaveral. This system was used for the inspection of the same three Centaur vehicles that were inspected in San Diego. Approximately 50% of the area of the foam was inspected on the Centaurs at Cape Canaveral. The most recent inspection required only about five hours, corresponding to a rate of 60 ft^2/hr. No disbonds have been found, indicating that the quality of the foam application process has been sufficiently proven that no further routine inspections are planned.

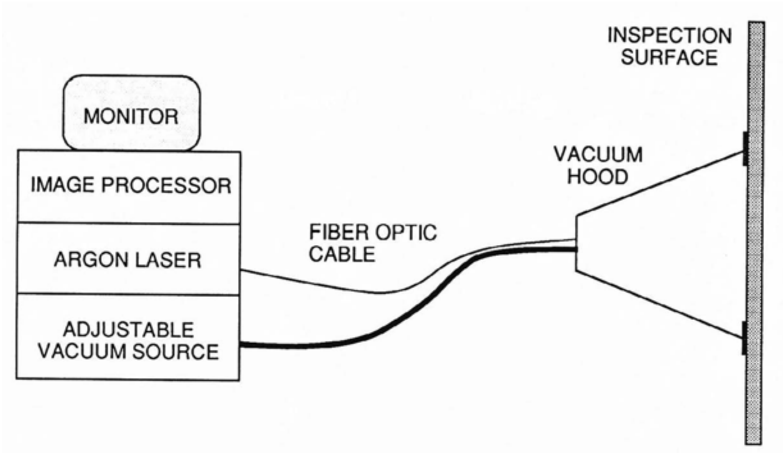

Fig. 6. Schematic of laser shearography with fiber optic connector and conical vacuum hood.

CONCLUSION

A difficult NDT problem was presented, that of detecting disbonds in the adhesive bondline between a 0.6-inch-thick foam insulation and a 10-foot-diameter 0.016 stainless steel cryogenic fuel tank. Various NDT techniques were evaluated and laser shearography was identified as a unique solution to the problem.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of John Newman and John Tyson of Laser Technologies, Inc. (LTI) of Norristown, PA and John W. Smith III of GDSS at Cape Canaveral, FL.

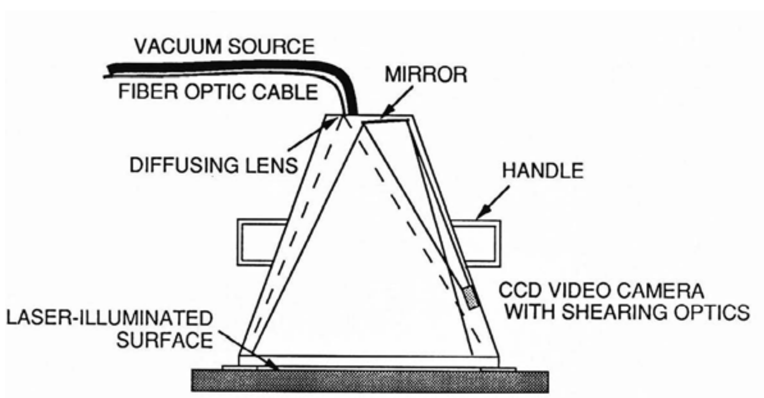

Fig. 7. Conical vacuum hood.

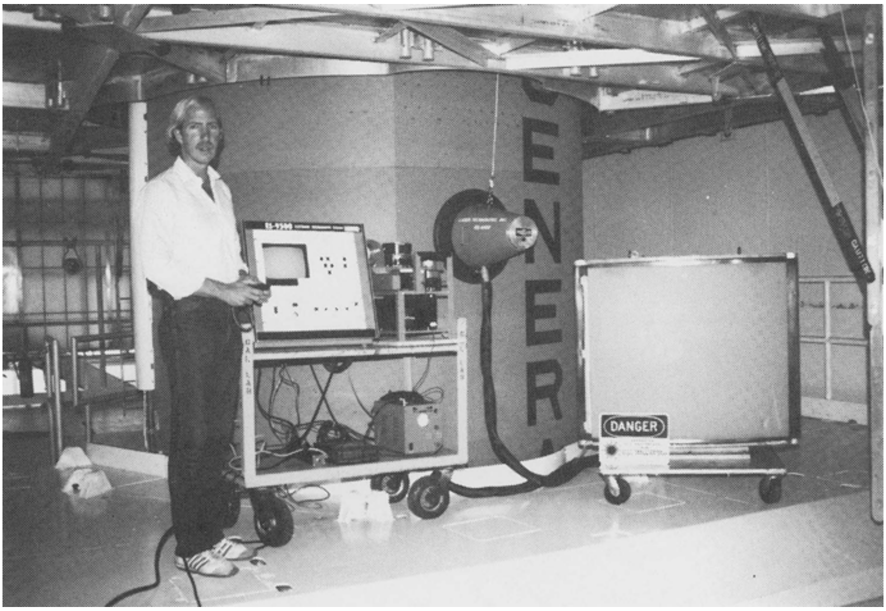

Fig. 8. Laser shearography test equipment on the launch pad at Cape Canaveral. Note the NDT standard at right.

REFERENCES

1. Y. Y. Hung, "Shearography: A New Optical Method for Strain Measurement and Non-Destructive Testing," *Optical Engineering*, May/June 1982, pp. 391–395.

2. J. W. Newman, "Production and Field Inspection of Advanced Materials with Holographic and Speckle Interferometry," SPIE, Vol. 814, *Photomechanics and Speckle Metrology*, 1987, pp. 421–427.

3. D. K. Das-Gupta, "Electronic Speckle Shearing in the Detection of Delamination in Composite Materials," SPIE, Vol. 805, *Optical Components and Systems*, 1987, pp. 144–151.

4. D. D. Burleigh, J. E. Engel, "NDT of an Adhesively Bonded Fixed Foam Insulation for Atlas/Centaur Cryogenic Fuel Tanks," Proceedings of 6th NASA Workshop/Conference, Houston, May 1989.

5. J. E. Engel, D. D. Burleigh, "Validation of Laser Shearography Testing for Fixed Foam Insulation Bonds," Review of Progress in Quantitative Nondestructive Evaluation, Bowdoin College, July 1989, published 1990 in Proceedings Volume 9A, pp. 569–576.

6. D. D. Burleigh, D. R. Kuhns, J. E. Engel, "Electronic Laser Shearographic NDT of a Foam Insulated Cryogenic Fuel Tank and Other Aerospace Structures," presented at ASNT Fall Conference, Valley Forge, PA, October 10, 1989.

7. D. D. Burleigh, J. E. Engel, "Shearographic NDT of Foam Insulation for Cryogenic Fuel Tanks," ASNT spring conference (Orlando) proceedings, p. 266, April 2, 1992.